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SYNOPSIS Some seriously cracked and leaked earth dams in China have been successfully strengthened by the cast-in-situ concrete diaphragm at or near the dam axis through the dam embankment. The diaphragm is enabled to seal the leakage through concentrated seepage path in the earthfill resulted from the large voids or the cracks in cohesive earthfill as well as the leakage through the alluvium in dam foundation. The effectiveness of this strengthening method depends on the correct determination of the major seepage channels. Serious longitudinal cracks have occured in some dams during excavating the slurry trenches and pouring concrete into them owing to the hydraulic fracturing effect of the drilling fluid and liquid concrete. After some modification of the construction technique the strengthening work was carried out smoothly. The cracks were closed after completion of construction work and the contact between the earthfill and diaphragm was satisfactory.

INTRODUCTION

Since the founding of the People's Republic of China in 1949, 18595 dams higher than 15 m, including 98 dams higher than 60 m, were completed in the whole country. They are mainly of the embankment dam type. Most of them have been performing satisfactorily, but a few of them cracked and leaked seriously and needed to be strengthened.

In China, the cast-in-situ concrete diaphragm wall had been used to build the antiseepage barrier in sand-gravel alluvium comprising the earth dam foundation in 1958 firstly and comesto be very popular in hydraulic engineering very soon. According to the imcomplete statistics by 1982, 61 cast-in-situ concrete diaphragms with a antiseepage area of about 444,000 m^2 have been completed, and 16 of them have a depth more than 40 m. The maximum depth is up to 68.5 m (Chen G. Y., 1978).

Since 1965, it had adopted to strengthen the damaged earth dams in order to seal the harmful leakage through both the embankment and its foundation. Completed diaphragms through embankments are listed in table 1.

The defects in fractured and leaked earth dams can be concluded as the seepage channels resulting from the concentration of coarse particles of gravelly soils and the tensile cracks in cohesive fills, as well as the alluvium in dam foundation. Besides excavating and backfilling, the measures available for strengthening these damaged dams are fracturing grouting with clay grout and cast-in-situ concrete diaphragm. A thin clay seams extending along the direction normal to the direction of minor principal stress are formed by the hydraulic fracturing effect of the pressure grouting and can seal the leakage through the earthfill itself (Bai Y. N. et al., 1981, Chen Y.J., 1980, 1982). This paper only presents the cases of using the cast-in-situ concrete diaphragms.

CASES OF CAST-IN-SITU CONCRETE DIAPHRAGMS THROUGH EMBANKMENT OF EARTH DAMS

The cast-in-situ concrete diaphragms listed in table 1 can be divided into three kinds as follows.

1. The main seepage channels are formed by the concentration of coarse particles of the weathering gravelly soils for the dam body, such as Chengbihe (Baise Prefecture Hydro, 1978), Hongchaojiang etc.

The Chengbihe earth dam with a height of 70 m and a reservoir capacity of 1130 X 10^6 m^3 was completed in 1961. The installed capacity of hydropower station is 26 MW. A central core of cohesive soils had been established in the earth dam up to the elevation 150 m, while a homogeneous dam with weathering gravelly soils had been adopted for the rest part, see Fig. 1.

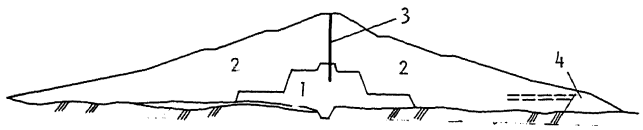

Fig. 1 Cross Section of Chengbihe Earth Dam
1. Central clay core; 2. Gravelly soil; 3. Concrete diaphragm; 4. Rockfill drainage prism

During the first filling of the reservoir, serious leakage had appeared at the downstream slope of the earth dam and comes to be more serious as the water level in the reservoir were raised. In 1961, there are three places of concentrated seepage at the downstream slope at elevation 173-174 m, while the corresponding upstream water level was 176.7 m. In 1971, the upstream water level had raised to 181.5 m, and the exit seepage area accounted for 4315 m^2, 10% of the total area of downstream slope. Total seepage was about 3.34 l/sec. The depression line and the exit point were raised every year. It was seriously imperiling the safety of the earth dam in the view of sliding and seepage failure. The main sourses of the harmful leakage could be concluded in the poor quality of the earthfill and the local concentration of coarse particles, as well as the poor contact between layers. There had not been provided any chimney drain to lower the

Table I. Completed Cast-in-situ Concrete Diaphragms through the Earth Dam Embankment

No.	Project	Dam type	Dam height m	Depth of Alluvium m	Max. depth of diaph-ragm, m	Thick-ness of diaph-ragm, m	Applied water head, m	Water head during const-ruction m	Anti-seepage area, m^2	Year of Comple-tion
1	Jinchuanxia	H	35	32	38	0.7	22.8	19	4480	1966
2	Bikou	CC	101	34	68.5	0.8	60.0		7865	1973
3	Chengbihe	H	70	-	55.2	0.8	60.0	57	14175	1974
4	Huangyanghe	CC	52	7.6	64.4	0.8	52.5	15	5430	1974
5	Miyun, auxiliary	SC	15.7	19	29	0.8	30.0	6	1590	1974
6	Nanyin	CC	40.5	10.5	49.5	0.8		20.5	8800	1975
7	Hongchaojiang	H	33	-	34	0.65	31.2		4411	1976
8	Haizi	H	28	19	44	0.8	26.5	13	13157	1976
9	Beitaishang	H	28.6	41	49	0.7	30		15101	1977
10	Zhaling	CC	62	-	61.2	0.8	43	35	30000	1978
11	Qiuzhuang	H	24.5	40	61.5	0.8	22.4		37400	1982
12	Yuqiao	H	23.5	10-20	33.2	0.8	14.4		3448	1982

H: Homogeneous; CC: Central core; SC: Sloping core

depression curve effectively.

By a detailed comparison with establish a slope core, fracturing grouting and chemical grouting in both technical and economical aspects, the cast-in-situ concrete diaphragm from dam crest down to the clay core in the lower part of earth dam had been accepted finally. The construction work was going on under the condition of reservoir filling. It started in 1972 and ended in 1974. The crest length of the diaphragm is about 400 m and was devided into 60 trenches. The volume of concrete poured was 17146 m^3. The observed data showed that the seepage at downstream slope decreased during construction and ceased finally as the diaphragm was completed. The depression curve in dam body and seepage exit point were lowered for about 15-20 m. The problems of dam safety due to sliding and seepage failure had been solved successfully. Then the reservoir is put into normal operation.

2. Fracture and leakage or other defects in clay core, such as Zhaling, Bikou etc.

Zhaling earth dam with a height of 62 m and reservoir capacity of 7170 X 10^6 m^3 is a earth dam of central core type. The installed capacity of hydropower station is 180 MW and the designed irrigated area is 30000 ha. The cross section of the earth dam is shown in Fig. 2.

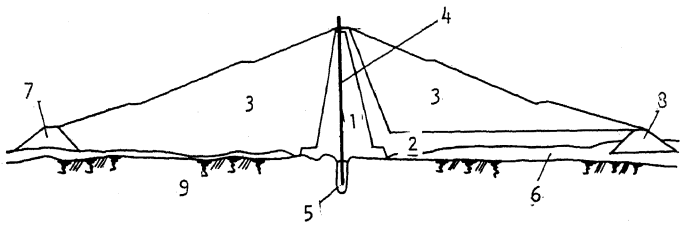

Fig. 2 The Cross Section of Zhaling Earth Dam
1. Clay core; 2. Sand gravel drain and filter; 3. Ballast; 4. Concrete diaphragm; 5. Grout curtain; 6. Alluvium in dam foundation; 7. Rockfill cofferdam; 8. Rockfill drainage prism; 9. Bedrock.

The construction work started in 1958, but was suspended for 8 years from 1962 to 1970. The earth dam was completed in 1971, and reservoir was filled in 1972. The clay core located at seriously weathered rock formation with developed fractures and faults, the water acceptance of which was greater than 10 Lugeon, even down to a depth of 50 m locally. Owing to the poor quality of the earth fills, the cracks appeared in construction stage, poor quality of the grout curtain, local big pore voids due to exist of weathered slat brock etc., the upstream water level were limited to a lower level in the aspects of dam safety. A cast-in-situ concrete diaphragm within the clay core was accepted as the main strengthening measure. A row of holes within the diaphragm was provided at some sections to allow the additional grouting of foundation rock. The crest length of the diaphragm is about 600 m. It was divided into 60 trenches. The volume of concrete poured into the slurry trench was 38248 m^3. The construction work started in December 1974 and ended in January 1978. Now the reservoir operated normally, which showed that the diaphragm appears to be very effective (Li Z.P., Wu X.Y., 1983).

3. Leakage through both embankment and dam foundation or abutment, and the strengthening work also needed for both, such as Huangyanghe, Nanyin, Haizi, Beitaishang etc.

Nanyin earth dam is of a central core type dam with a height of 42 m and a reservoir capacity of 16 X 10^6 m^3, see Fig. 3. During the first filling of the reservoir in 1971, the phenomena of sand boiling and piping were taking place at the downstream side of the earth dam due to the poor quality of earth fills and remained alluvial deposit in dam foundation with a thickness of 3 - 10 m. The longitudinal cracks also occured at dam crest. The earth dam was seriously damaged. A cast-in-situ concrete diaphragm wall within the central core extended from the dam crest down to the bed rock through the embankment, alluvial deposit and weathered rock was used as the basic strengthening measure to reestablish the antiseepage system.

The diaphragm has a crest length 213.6 m, antiseepage area 8800 m^2, total borehole length 11930 m, volume of concrete 9506 m^3. The maximum depth of diaphragm is 49.5 m, and the average depth is 44 m. Construction work

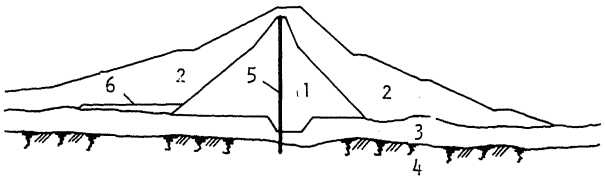

Fig. 3 Cross Section of Nanyin Earth Dam
1. Loam core; 2. Sand gravel shell; 3. Alluvial deposit in dam foundation; 4. Bedrock; 5. Concrete diaphragm; 6. Blanket of loessial soils.

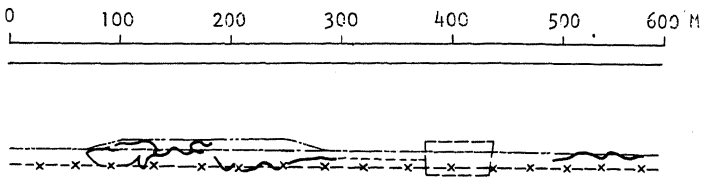

Fig. 4 Cracks at Dam Crest of Zhaling
—— Upstream Boundary of Central Core
--*-- Axis of Dam
- · - Axis of Central Core
-·-· Axis of Concrete Diaphragm
Grouting Gallery

started in February and ended in November 1975. The diaphragm seems to be very effective in sealing the serious leakage. The seepage through the main dam and its foundation accounted for only 16.38 l/min at the upstream water level near the normal high level. The reservoir was put into normal operation for years.

Among the cases of building concrete diaphragm in dam embankment, only a few were not possessed of positive result due to unsuccessfully cut off the major seepage channels. For example, Haizi earth dam founded on limestone with karst caverns. Serious leakage had been observed after filling of reservoir. A row of holes precasted within the diaphragm was provided for the grouting operation of the bedrock. Therefore, the effectiveness of such diaphragm is closely related to the correctness of determination of the main seepage channels. For these reasons, it is absolutely neccessary to make sure of the geological conditions, the quality of earthfill, the data obtained from seepage observations etc. and review these data carefully for correctly selecting the strengthenging measures.

HYDRAULIC FRACTURING EFFECT AND CRACKING IN EMBANKMENT DURING CONSTRUCTION

In the process of construction of the diaphragms at Chengbihe, Nanyin, Zhaling earth dam, the cracking in earthfills and leaking of drilling fluid and liquid concrete from the slurry trenches had taken place, especially at Zhaling earth dam.

At the beginning of the construction works at the dam crest of Zhaling earth dam, because of the lacking of practical experiences under such condition, the same principles as building diaphragms in dam foundation were adopted, such as filling the trench fully with drilling fluid, pouring concrete as quick as possible, excavating the trenches in primary and secondary order etc. This is the main reason for appearing serious cracks. In most cases leakage of slurry had taken place firstly, and followed by surface cracking, which had quickly been widened in the process of concrete pouring. The cracks were closed after set of concrete. The surface cracks had been developed along the axis of central core and throughout the whole dam crest, see Fig. 4. The dip angles of the cracks are very step and accounted for more than 75° - 80° dip to upstream side. The cracks extended from dam crest down to the dam base. Their width varied, but not decreased with the depth, see Fig. 5.

The most serious cracks have a width of 25-30 cm and a differential settlement between the soil mass in both side of 20 - 25 cm. It must make sure if there will be a

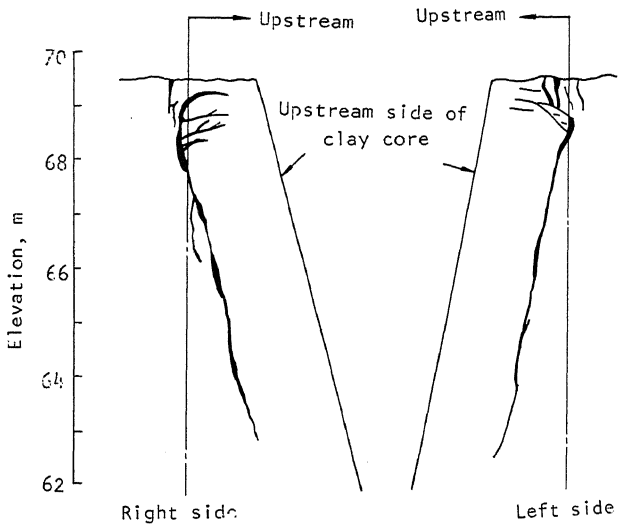

Fig. 5 Crack Pattern at Walls of Pit No. 2

sliding occured or if the cracks will cross the central core. A borehole No. 10 had drilled at 1.4 m upstream from the surface crack. The drill cores with slurry or concrete had been got from depth 5.29-5.55, 5.62-5.90, 6.50-6.64, 16.29-17.97, 20.1-33.45 m from dam crest. An additional borehole No. 12, located at 1.0 m upstream from borehole No. 10, hadn't found out any cracks filled with slurry. It showed that the cracks extended downward nearly vertically. Not only slurry, but also concrete had filled the cracks, which showed that the cracks were expanded during concrete pouring.

Three rows of surveying mark located at the dam crest and slope had been installed for every slurry trench in order to make observation of the relation of fracturing to the horizontal movement of the dam during concrete placing. If the concrete placing work have gone normally, the upstream and downstream parts of the dam body moved upstream and downstream respectively with a maximum horizontal displacement of 41 mm. The dam body recovered

to the original position after ending of the concrete placing.

There are two different ways to approaching the mechanisms of forming cracks. The first is reopenning and expanding of the minor fractures already existed. The second is newly fractured under the pressure of slurry and liquid concrete, known as the phenomena of hydraulic fracturing. The latter seems to be correct for the following reasons:

1. The fracturing pattern of the cracks. All the cracks are nearly perpendicular to the direction of minor principal stress and meander the dam axis. They extended downward to the dam base vertically. The width of the cracks are variable, but no tendency to decrease with depth.

2. The process of crack forming. Generally, the drilling fluid leaked during excavating the trench at first, then the cracks appeared at the dam crest and expanded during concrete placing. The first fractured place located at about 1/3 dam height. At this point, the ratio of minor principal stress and overburden pressure is a minimun.

3. All cracks were filled with slurry and closely contact with the surrounding soil mass. The cracks opened during pouring concrete and closed after completion of pouring. It agreed with the data obtained from displacement observation.

4. Fracturing was lightened or ceased as the fluid pressure had been reduced by some engineering measure.

According to the analysis of the mechanism of the possible fracture, some modified procedures were taken to solve these problems.

1. Control the slurry level in the trench not higher than the bottom of the guide wall at top end of the trench and the density of the slurry not exceed 1.15 g/cm3 in order to reduce the fluid pressure;

2. Control the pouring speed not exceed 1 m/hr. and timely pumping out the slurry replaced by concrete in order to reduce the combined fluid pressure due to both liquid concrete and slurry.

3. Trench excavation was completed by three orders, e.i. two excavating trenches apart from each other at least a distance of two trench length.

4. At the moment of leaking slurry or concrete, the construction works were stopped temporarily until the leakage was ceased.

The prohlems related to cracks and leakage were effectively solved by adopting these measures. Thereafter the construction works had gone on smoothly till completion. It had shown that the hydraulic fracturing was the main cause of cracks and the measures adopted according to this phenomena were correct.

CONCLUSION

Above-mentioned practical cases have shown that the cast-in-situ concrete diaphragm is effective for strengthening the damaged dams in the view of antiseepage. The construction works can be done under the condition of reservoir filling. Both the leakage through embankment and dam foundation can be sealed with high quality. Many experiences are gained throughout a lot of projects. This is an effective and practical measure for sealing the leakage of completed dams. Attention must be concentrat to cut off the main seepage channels.

During construction stage, cracks and leakage of slurry and concrete had been happened because of the hydraulic fracturing effect. The problems had been solved by adop ing some modification in construction technique to reduc the fluid pressure. Thereafter, the construction work had gone on smoothly.

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